This article is reprinted from the TRANSACTIONS of the ASAE (Vol. 32, No. 1, pp. 147-154, 160, 1989)
Published by the American Society of Agricultural Engineers, St. Joseph, MI 49085-9659 USA

Sprinkler Irrigation Management for Corn — Southern Great Plains

T.A. Howell, K.S. Copeland, A.D. Schneider, D.A. Dusek
MEMBER ASAE MEMBER ASAE

ABSTRACT

IN the Southern Great Plains, sprinkler-irrigated corn (*Zea mays* L.) yield is often limited by the irrigation water supply capacity. A field experiment conducted in 1987 determined sprinkler-irrigated corn responses which were used to modify and calibrate the CERES-Maize corn growth model. This validated model was then used to simulate corn water use and yield for various levels of irrigation water supply capacity. Effects of management decisions such as allowed soil water profile depletion and net irrigation application amount were studied. The yield, water use, and water use efficiency of fully-irrigated corn were 11.7 Mg/ha, 838 mm, and 1.40 kg/m^3, respectively; and all decreased with irrigation deficits. The modified CERES-Maize model accurately simulated evapotranspiration, aerial dry matter yield and grain yield of the corn experiment. A 28-year simulation (1958-1985) at Bushland, TX, indicated that a net sprinkler irrigation supply capacity of 8 mm/d is necessary to avoid irrigation system related yield constraints on the slowly permeable Pullman clay loam soil. During those 28 years, a net irrigation supply capacity of 4 mm/d only reduced the mean yield by 12.5% from 11.15 Mg/ha to 9.75 Mg/ha but more than quadrupled the variance of the corn yield. With adequate net irrigation supply capacity, irrigation application amount (for 1- to 4-day irrigation frequencies) and allowed soil water depletion (up to 50% of the plant extractable soil water) did not greatly affect simulated crop yield but greatly affected the hydrologic efficiency for storage of precipitation and the net irrigation water requirement.

INTRODUCTION

In the Southern Great Plains, irrigation is necessary for economic production of corn. The Southern Great Plains region is defined as the High Plains of Texas, New Mexico, and Oklahoma that overlay the Ogallala aquifer. Musick et al. (1988a) and Musick et al. (1988b) have summarized the irrigation trends in the Texas High Plains portion of the Southern Great Plains. For the period from 1958 to 1984, they reported that corn was the third largest irrigated crop in the northern portions of the Texas High Plains in terms of land area; but of the three major irrigated crops (winter wheat, grain sorghum and corn), the greatest water depth was applied to corn. They reported sprinkler irrigation was used on 37% of the total irrigated land area in 1984 and that the amount of sprinkler irrigation remained stable despite a region-wide decrease in irrigated land. Center pivot sprinkler systems are the common mode of sprinkler irrigation in the area, and graded furrow systems are the most common surface irrigation method. Musick et al. (1988a) reported that irrigated grain sorghum land area declined by 0.44 million ha in the central Texas High Plains from 1964 to 1979 and was replaced with 0.26 million ha of irrigated corn. The irrigated corn area peaked in this region at 0.52 million ha in 1976-77 and declined to about one-half of the peak area by 1984. Although the decline in irrigated corn area can be attributed to many factors, certainly the realization of the high irrigation water demands in combination with escalating energy prices, declining well capacities, and falling commodity prices played key roles in grower decisions. Clearly, the summer droughts of the seventies (1976-77) and the drought in the region in 1980 illustrated the need for careful irrigation management on corn in order to obtain high production. In addition, as Musick and Dusek (1980) discussed, water can not be as successfully "stretched" (limited or deficit irrigation) with corn in this region as commonly practiced with cotton, winter wheat and grain sorghum.

The purpose of this article is to: (a) summarize experimental results from a sprinkler irrigation study of corn at Bushland, TX; (b) calibrate the CERES-Maize corn growth model for conditions in the Southern Great Plains; and (c) evaluate sprinkler irrigation management options for corn in this region, in particular, the effect of water supply capacity in terms of crop yield, irrigation requirement and net irrigation application.

LITERATURE REVIEW

Although numerous studies of the relationship between irrigation and water use and yield of corn have been conducted worldwide [i.e. Doorenbos and Kassam (1979) referenced 50 corn related water studies nearly 10 years ago], only three studies have reported such research in the Southern Great Plains. Musick and Dusek (1980) reported seasonal ET values between 667 mm and 789 mm for fully-irrigated corn at Bushland from level-basin studies for 3 years with corresponding grain yields of 9.5 Mg/ha to 10.9 Mg/ha. They reported fully-irrigated seasonal water use efficiency (grain yield per unit ET) values of 1.25 kg/m^3 to 1.46 kg/m^3. Eck (1984) reported that the ET of corn at Bushland varied

Article was submitted for publication in August, 1988; reviewed and approved for publication by the Soil and Water Division of ASAE in November, 1988. Presented as ASAE Paper No. 88-2098.

Contribution from the USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX.

The authors are: T.A. HOWELL, Agricultural Engineer, K.S. COPELAND, Biological Technician, A.D. SCHNEIDER, Agricultural Engineer, and D.A. DUSEK, Agronomist, USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX.

from 783 mm to 1,003 mm over 4 years of study conducted in both graded furrow and level-basin plots, with maximum yield levels from 8.4 Mg/ha to 13.2 Mg/ha. Undersander et al. (1985) conducted sprinkler irrigation studies with corn at Bushland and Etter, TX, under similar conditions. They reported mean grain yields of 5.54 Mg/ha and a mean water use of 791 mm. These studies indicate that irrigated corn has much greater ET in the Southern Great Plains than in many other locations in the U.S.; and, therefore, the irrigation management, as well as the irrigation supply capacity, should be critical in this region.

With sprinkler irrigation, the water conveyance is by pressurized pipe lines, but the final water conveyance to the soil and crop is affected by the windspeed and direction which can greatly distort the application pattern. The Southern Great Plains is one of the windiest regions in the United States. Both the application efficiency and uniformity are affected by the atmospheric conditions. In addition, surface soil water conditions resulting from antecedent rains and/or irrigation and soil surface physical conditions resulting from tillage greatly affect infiltration from sprinkler applications. Lyle and Bordovsky (1983) reported that the mean sprinkler application efficiency for 2 years in this region was 81% for conventional tillage and was 84% for basin tillage. They also reported that low energy precision application (LEPA) increased the mean application efficiency to 88% and 99% for conventional and basin tillage, respectively. Undersander et al. (1985) reported a mean sprinkler application efficiency of 77% for two sprinkler application methods at two locations and for three years in this region. Musick et al. (1988b) reported that the mean sprinkler application efficiency from 223 center pivot evaluations in this region was 83% and that the mean distribution uniformity was 73% [the equivalent Christiansen's uniformity would be 83% based on Warrick (1984)].

Sprinkler irrigation management, particularly for center pivot systems, is simpler in some ways than traditional graded furrow irrigation management. The primary sprinkler irrigation management decisions are the mode of application (sprinklers, spray nozzles, LEPA, etc.), the allowed soil water profile depletion before irrigation and the irrigation application amount. In addition, methods of tillage can affect the net retained irrigation water as well as retained precipitation. The irrigation application amount is constrained by the desired irrigation interval and the irrigation water supply capacity. The irrigation water supply capacity is a major constraint for spinkler irrigation in the Southern Great Plains. In economic terms, irrigation in much of the Southern Great Plains is "water limited" rather than "land limited" since often the optimum amount of irrigation water is constrained by the water supply rate (Seginer, 1983). Stegman and Shah (1971) determined by extreme-value analysis that the net sprinkler design capacity for the Oakes area of North Dakota should be 6.4 mm/d, but they determined by simulation analysis that the net sprinkler capacity should be 4.6 mm/d. Heermann et al. (1974) used a 60-year water balance simulation to examine irrigation capacities for corn in eastern Colorado. They reported that most center pivot systems in the Central Great Plains had supply capacities of 9 mm/d. They determined that the system capacity would depend on the allowed soil profile water depletion, and they reported that a net irrigation system capacity of 5.8 mm/d should be sufficient for eastern Colorado. Von Bernuth et al. (1984) studied the irrigation system capacity for corn in Nebraska with a water balance and yield model. They simulated corn production for several locations in Nebraska, as well as different soil conditions for up to 30 years at some locations. They developed cumulative probability density functions for soil water profile depletion and yield for several locations in Nebraska.

Crop growth models are suitable for many irrigation decision analyses. Kundu et al. (1982) used the CORNGRO model (Childs et al., 1977) to determine optimum soil water depletion and irrigation application levels as well as optimum irrigation timing. Many crop growth models for corn have been developed [for example, see Duncan, 1975 (SIMAIZ); Baker and Horrocks, 1976 (CORNMOD); Stapper and Arkin, 1980 (CORNF); Morgan et al., 1980; Lambert and Reicosky, 1984 (TROIKA); Jones and Kiniry, 1986 (CERES-Maize); Stockle and Campbell, 1985; and Dierckx et al., 1988] which are capable of simulating the effects of irrigation decisions on corn production.

PROCEDURES

Experimental

An experiment was conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX, in 1987 to determine the corn yield and water use under sprinkler irrigation in the semiarid environment of the Southern Great Plains. The soil at the site is classified as Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls) and is described in detail by Unger and Pringle (1981) and Taylor et al. (1963). This soil is common to over 1.2 million ha of irrigated land in the region, including about one-third of the sprinkler-irrigated lands in the region (Musick et al., 1988b). The land slope of the field is 0.3%.

A short, 3-span Lockwood* center pivot sprinkler system (135 m in length) was used in the study. The system was equipped with Senninger low-angle, impact sprinklers (model 5006) with variable spacings and variable nozzle sizes. The sprinkler nozzles were changed and some sprinklers relocated on the second and third spans to apply a constant sprinkler flow rate of 0.44 L/s at a 5.64-m spacing, with a resulting decreasing irrigation application pattern outward from the first tower (Fig. 1). The pivot operating pressure was approximately 220 kPa, and the flow rate was 6.3 L/s. Five plots were located radially outward from the pivot point and in each quadrant of the west one-half of the pivot field (Fig. 2). The east half of the pivot field was fallow. The field had previously been in uniformly-irrigated grain sorghum for 4 years. Neutron access tubes (38 mm I.D. electrical, mechanical tubing 3.0 m in length) were installed to a depth of 2.9 m in the center of each plot with a tractor-mounted Giddings soil sampling

*Mention of a trade name or product does not constitute a recommendation or endorsement for use by the U.S. Department of Agriculture, nor does it imply registration under FIFRA as amended.

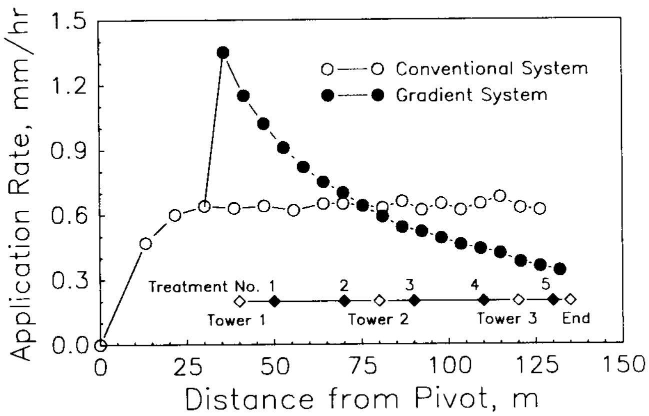

Fig. 1—Application rate (sprinkler flow rate per unit land area of sprinkler spacing) along the center pivot system.

machine. Irrigation and precipitation were measured at each neutron site, with digital recording rain gauges (Digirain) mounted 2.0 m above the soil surface. The irrigation treatment plots were located at distances away from the pivot point such that treatment 1 received a full irrigation application amount and treatment 5 received approximately 30% of irrigation treatment 1 and the intermediate plots received nearly proportional amounts. The plots were irrigated weekly, depending on precipitation, with irrigation amounts computed from the measured soil water depletion necessary to refill the profile in treatment 1. The soil water content was measured weekly with a Campbell Pacific neutron probe (503DR Hydroprobe) at 0.2-m increments from 0.2 m below the soil surface to a 2.4-m depth using 15-s integrations. The neutron probe was field calibrated. Water use estimates of ET were computed by water balance, assuming that drainage was negligible and estimating runoff. Only one rain event and one irrigation event produced runoff from the field; neither event was significant.

Corn (cv. Pioneer 3124) was planted on April 21, 1987, in 0.76-m spaced rows in a semicircular pattern around the pivot point. Nitrogen fertilizer was preplant applied uniformly at a rate of 180 kg N/ha in the NH_3 form. Dual herbicide (Metolachlor:2-chloro-N-(2-ethyl-6-methyl-

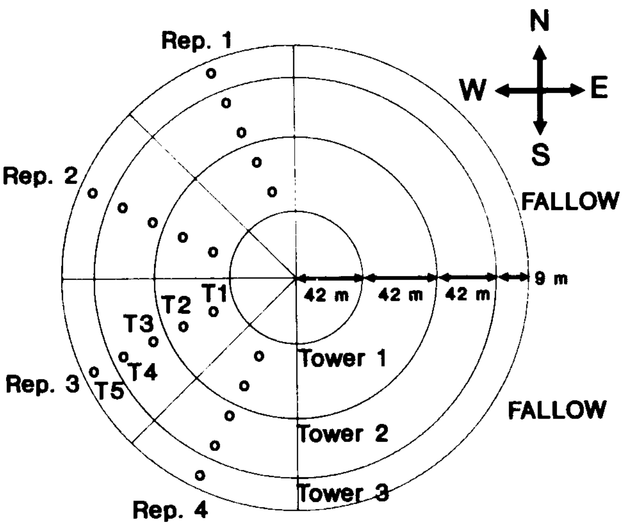

Fig. 2—Plot diagram and field arrangement.

phenyhl)-N-(2-methoxy-1-methyl-ethyl) acetamide) was applied at 3.4 kg active ingredient/ha for weed and volunteer sorghum control. Small furrows were formed between the rows when the field was cultivated. The final plant density was 5.5 plants/m^2. A 40-mm irrigation was applied uniformly on April 22 to the plots following planting for germination. The next two irrigations of 28 mm and 24 mm, respectively, were applied uniformly on May 1 and June 16. The first treatment irrigation was applied on July 8. The mean of the "net" irrigation applications and precipitation (planting to harvest) received by each treatment was 835 mm, 775 mm, 704 mm, 673 mm, and 663 mm for treatments 1 through 5, respectively.

Plant samples were collected periodically from three of the replications on June 1, June 25, July 13, August 3 and August 31. Each plant sample was harvested from 1.0 m of row from two adjacent rows (total land area 1.52 m^2). The harvested plants were counted and separated into the component parts of leaves, stems, and ears. Leaf area of a subsample of leaves was measured with Li-Cor optical integrator (model 3100). All plant material was dried at 70°C, and the leaf area index and dry matter were computed. The plots were hand-harvested on September 30 using samples of 3 m of row from two adjacent rows (total area of 4.56 m^2). Total aerial dry matter was harvested, ears were counted and separated, and the stover was chopped and a subsample of the chopped stover was dried at 70°C. Grain was hand shelled, and the mass of 1,000 seeds was determined. Grain yields are reported at 15.5% water content (wet basis). In each plot, four rows were combine-harvested on October 5, and plot yields were determined by weighing the harvested grain in a Brent weighing yield cart (model 150). Subsamples of grain were taken from the combine harvests of each plot for water content measurements.

Simulation

The CERES-Maize corn growth model (Jones and Kiniry, 1986) (standard version) was used for the simulation analyses. This model has been used to estimate regional corn production (Hodges et al., 1987), drought assessments (Du Pisani, 1987), and for analysis of irrigation decisions in humid regions (Boggess and Ritchie, 1988). The standard model version does not include fertility simulation. The model computes net daily photosynthesis based on intercepted light and partitions the photosynthate into the various organs. Leaf area is estimated based on growing degree units and constrained by photosynthate partitioning and temperature. Leaf area senescence is simulated based on water stress and maturity effects. Soil water evaporation and crop transpiration are computed basically according to Ritchie (1972) but using a modified Priestley and Taylor (1972) potential ET equation instead of the combination equation. Runoff is estimated by the modified SCS (USDA-SCS, 1972) procedure used in the EPIC model described by Wiliams et al. (1984). The CERES-Maize model uses a layered soil profile and accounts for drainage through the profile. Crop growth is reduced by temperature and soil water deficit effects. Grain mass and grain number are computed in the model. The model operates on a daily time step and

TABLE 1. Description of Pullman Clay Loam Soils Data and Plant Genetic Data for the CERES-Maize Model

	Soil profile layer number 1	2	3	4	5	6	7	8	9
Layer depth, m	0.15	0.15	0.15	0.30	0.30	0.15	0.15	0.15	0.30
Lower limit, %†	11.0	19.2	19.2	17.9	18.1	18.2	18.8	21.2	24.0
Drained upper limit, %	32.7	33.1	32.1	32.7	33.6	27.0	25.3	26.3	26.3
Saturated water content, %	45.0	45.0	45.0	40.0	40.0	38.0	35.0	35.0	35.0
Plant rooting weighting factor	0.90	0.64	0.47	0.35	0.17	0.11	0.08	0.06	0.00

Soil parameter	Profile value
Lower limit, mm	341
Drained upper limit, mm	543
Saturated limit, mm	710
Plant-extractable water, mm	202
Soil albedo, %	19
Upper limit stage 1 evaporation, mm	8
Stage 2 evaporation constant, mm/(day$^{1/2}$)	3.5
SCS runoff curve number	82
Profile drainage constant, L/day	0.05

Plant parameter	Value
Seeding depth, m	0.05
Plant population, #/m^2	5.1
GDD‡ seedling emergence to end of juvenile	320
Photoperiod sensitivity coefficient, hr^{-1}	0.7
GDD silking to maturity	960
Maximum kernel number, #/plant	700
Potential kernel growth rate, mg/(kernel-day)	6.8

†Volume basis.
‡Growing degree day, base 8°C.

requires input data for weather, initial soils information, and initial plant genetic information.

The daily weather data required for the model was obtained at the Laboratory main weather station located approximately 0.8 km east of the plot area and is described by Steiner et al. (1987). The weather data included maximum and minimum air temperature, solar radiation, mean daily 2-m windspeed, mean vapor pressure deficit, and precipitation. Soils data (Table 1) for the model were the same as the data used by Steiner et al. (1987) except a 9-layer soil profile was used and other soil parameters were computed following the guidelines in Jones and Kiniry (1986). Plant genetic information (Table 1) was obtained from Jones and Kiniry (1986) and personal communications with Dr. J.R. Kiniry (USDA-ARS, Temple, TX).

Several subroutines in the CERES-Maize model were modified (Table 2). The modifications of importance are: (a) added the option to use the FAO-24 version (Doorenbos and Pruitt, 1977) of the combination equation to estimate "potential" ET along with the input of a proportionality coefficient to multiply times the computed potential ET for either the combination equation or the original modified Priestley-Taylor equation to simplify "calibration" of the water balance; (b) changed the leaf area computations to make the specific leaf area (green leaf area per unit dry leaf mass) more conservative according to Van Keulen (1986); (c)

TABLE 2. Modifications to Subroutines in the Standard Version of the CERES-Maize Corn Growth Model (Jones and Kiniry, 1986)

Subroutine	Modifications
WATBAL	Added the option to calculate potential ET by either the original model equations (modified Priestley-Taylor equations corrected for advection) or the FAO-24 version of the combination equation. The FAO-24 equation requires the input of additional weather data for windspeed and vapor pressure deficit.
	Added a coefficient (COEFF) to facilitate calibration of the potential ET calculations. The potential ET is computed as the following: EO = COEFF*EO.
PHASEI	Doubled the heat unit requirements for emergence to the following: P9 = 30. + 12.*SDEPTH
GROSUB	Modified the specific leaf area for ISTAGE 1 and 2 (emergence to tassel initiation) to 22.5 m^2/kg, and after ISTAGE 2 (tasseling to maximum leaf area) to 15.0 m^2/kg.

doubled the heat unit accumulation requirements for emergence; and (d) added irrigation management control options for long-term simulations. These modifications, although specific for this location, were needed to improve the performance of the model for conditions common to this region. The combination equation should improve ET estimates in highly advective environments like Bushland (Dugas and Ainsworth, 1985). The specific leaf area is generally a conservative plant characteristic and, therefore, the changes made in the model that affect the leaf area estimations by CERES-Maize should be generally applicable to other locations as well. The necessary change in the heat units for emergence as well as the change in the leaf area parameters may simply be a result of the manner in which heat units are accumulated by the model based on mean daily temperatures. The soil temperature in the rootzone is a major factor in determining plant emergence as well as plant growth early in the season. The mean air temperature may be a poor parameter to use in models like CERES-Maize to determine heat unit accumulations early in the season at locations like Bushland where the mean soil temperature lags mean air temperature.

The long-term simulations used actual weather data at the Bushland location for 1958 through 1985. Each simulated year began with either a full plant-extractable soil water profile or a uniformly one-half full soil water profile on April 1. A subroutine was added to simulate planting date based on planting no earlier than April 25 with delays for cool antecedent minimum temperatures (3-day mean less than 8°C) and 3-day antecedent rainfall exceeding 25 mm. Planting was delayed further if any rainfall occurred on that day.

RESULTS AND DISCUSSION

Experimental

The 1987 growing-season precipitation was 459 mm, which was approximately 20% above normal for Bushland. Table 3 presents a summary and statistical analysis of the yield and various yield components. Grain yield varied from 6.6 Mg/ha to 11.7 Mg/ha, aerial dry matter yield varied from 13 Mg/ha to 18 Mg/ha, seed

TABLE 3. Irrigation and Yield Data Summary

Treatment no.	Irrigation water, mm	ET, mm	Aerial dry matter yield, Mg/ha	Grain yield,† Mg/ha	Harvest index	Seed number, #/m^2
1	376	838	18.13a‡	11.70a	0.546a	3069a
2	316	794	17.27ab	10.98ab	0.537ab	3075a
3	245	738	15.85bc	9.63bc	0.514ab	2793ab
4	214	724	14.30cd	8.18cd	0.483bc	2459bc
5	204	689	12.97d	6.64d	0.433c	2091c
LSD 0.05			1.83	1.78	0.059	442

Treatment no.	Seed mass, mg/seed	Plant density, #/m^2	Ear density, #/m^2
1	322a	5.1a	5.4a
2	302b	5.5a	5.7a
3	292bc	5.6a	5.7a
4	281cd	5.5a	5.6a
5	268d	5.4a	5.4a
LSD 0.05	14	NS	NS

†Grain water content is 15.5% (wet basis).
‡Means followed by different letters are significantly different (0.05 level).

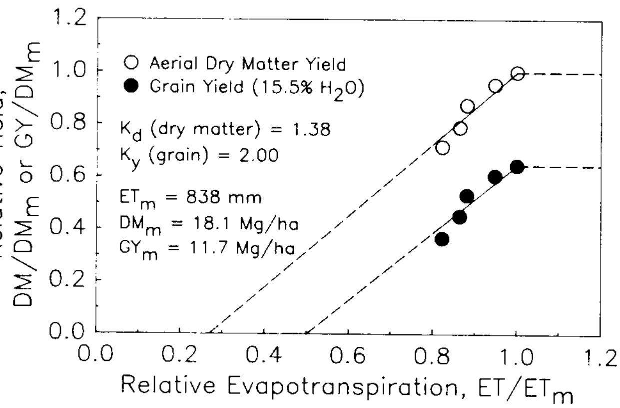

Fig. 3—Relationships of relative dry matter yield (DM/DM_m) and relative grain yield (GY/DM_m) to relative evapotranspiration (ET/ET_m) for each irrigation treatment.

number varied from 2,091 seeds/m^2 to 3,075 seeds/m^2, seed mass varied from 268 mg/seed to 322 mg/seed, and harvest index varied from 0.43 to 0.55, all with significant differences. Plant density and ear density were not significantly different among the treatments. The main effect of the imposed water deficits on grain yield was reduction of seed numbers, since late season rains reduced water deficits during grain filling, moderating the water stress effects on seed mass. Although the harvest index varied among irrigation treatments, the grain yield was highly correlated to total aerial dry matter (r = 0.975). The combine-harvested grain yield (data not shown) was correlated to the hand-harvested grain yield (r = 0.90) but was about 7% lower. The mean measured crop water use for treatments 1 through 5 was 838 mm, 794 mm, 738 mm, 724 mm and 689 mm, respectively. The fully-irrigated seasonal water use efficiency was 1.40 kg/m^3 (treatment 1) and decreased with increasing irrigation deficits to 0.96 kg/m^3 (treatment 5).

The relationships of relative grain and relative aerial dry matter yields to relative evapotranspiration are shown in Fig. 3. Aerial dry matter yield was linearly related to ET [DM(Mg/ha) = $-10.44 + 0.035$ ET(mm), $r^2 = 0.939$]. Defining ET and DM from treatment 1 as ET_m and DM_m, respectively, relative aerial dry matter yield (DM/DM_m) was linearly related to relative evapotranspiration (Fig. 3) [$DM/DM_m = -0.58 + 1.60\ (ET/ET_m)$, $r^2 = 0.939$]. The regression coefficients were similar to values of -0.35 for the intercept and 1.33 for the slope reported by Wenda and Hanks (1981) for corn at several sites in Utah.

Grain yield was also linearly related to ET [GY(Mg/ha) = $-15.88 + 0.034$ ET(mm), $r^2 = 0.924$]. Again, defining GY_m as GY from treatment 1, relative grain yield (GY/GY_m) was linearly related to relative evapotranspiration (ET/ET_m) [$GY/GY_m = -1.36 + 2.40\ (ET/ET_m)$, $r^2 = 0.925$] (Fig. 3); however, both of the regression coefficients were quite different from those reported for several sites in Utah [slope = 1.46 and intercept = -0.51] by Wenda and Hanks (1981) indicating much greater grain yield sensitivity for corn to water deficits at Bushland. Doorenbos and Kassam (1979) defined a grain yield sensitivity factor, K_y, as the mean ratio of [$1 - (GY/GY_m)$] to [$1 - (ET/ET_m)$]. The value of K_y for our data is 2.00 which is larger than the mean seasonal value of K_y for corn of 1.25 from Doorenbos and Kassam (1979) but agrees with data from Musick and Dusek (1980) that indicated the corn grain yield threshold ET (the ET required for zero grain yield) was about 50% of ET_m at Bushland.

Hanks and Rasmussen (1982) defined the grain yield threshold ET as $\{[1 - (1/K_y)](ET_m)\}$ and indicated that it could be considered as the seasonal soil water evaporation. We believe that the argument is more logical if based on aerial dry matter yields. We defined a dry matter yield sensitivity factor, K_d, as the ratio of $[1 - (DM/DM_m)]$ to $[1 - (ET/ET_m)]$. Then the seasonal soil water evaporation would be given by $\{[1 - (1/K_d)](ET_m)\}$. The K_d value for our data is 1.38 which results in an estimated seasonal soil water evaporation amount of 230 mm (27% of ET_m).

Although shorter season cultivars were used in the previous irrigation studies at Bushland, the results from 1987 are representative of the response of corn to irrigation in the Southern Great Plains. Yield, water use and water use efficiency were comparable to the results by Musick and Dusek (1980) and Eck (1984). Sprinkler-irrigated corn grown on the Pullman clay loam soil responded similarly to the previous surface-irrigated studies, but our grain yields were considerably greater than those obtained under sprinkler irrigation by Undersander et al. (1985). The water use of sprinkler-irrigated corn is similar to that reported for the surface irrigation studies.

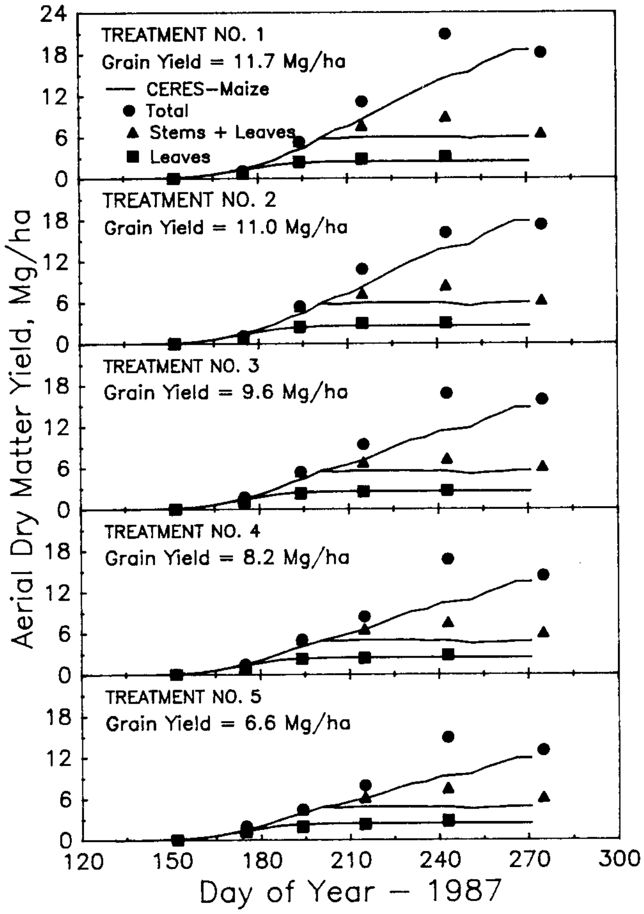

Fig. 4—Growth of corn and distribution of aerial dry matter between leaves, stems, and ears as measured (symbols) and simulated by the CERES-Maize model (lines) for each of the 1987 sprinkler irrigated corn treatments.

CERES-Maize Model Calibration

Corn growth, yield and water use computed with the modified version of the CERES-Maize model were compared to the 1987 experimental data. A chronology of the procedural adjustments made in the model, and data was: (a) the combination of plant genetic coefficients [mainly P1, P2 and P5 (defined in Jones and Kiniry, 1986)] was determined to match the phenology data for treatment 1 [silking and physiological maturity]; (b) adjustments were made in the subroutine GROSUB until the specific leaf area and computed leaf area index approximately matched the data from treatment 1 [16 m^2/kg to 22 m^2/kg for specific leaf area and leaf area index up to 4]; (c) the potential ET coefficient was adjusted until the soil water balance of all the treatments produced soil water profile extractions and seasonal ET values similar to the measurements; (d) the grain yield component plant genetic parameters [G2 and G3 (defined in Jones and Kiniry, 1986)] were adjusted until the seed numbers and seed mass agreed with the measured data. The potential ET adjustment coefficient of 0.87 for the FAO-24 ET version was found to produce the most acceptable water balance results, but the model results were practically the same using the standard model potential ET equation (modified Priestley-Taylor equation) and a correction factor of 1.15. The model crop genetic input parameters that resulted from the adjustment procedures are listed in Table 1. The model predicted accurately the dry matter development and partitioning between leaves, stems, and ears (Fig. 4). Apparently, the August 31 (DOY 243) samples were unrepresentative as compared to the final harvest data; however, the model accurately predicted the final aerial dry matter yield and grain yield. Fig. 5 shows a direct comparison between the simulated and measured seasonal ET, final aerial dry matter yield, and final grain yield. The model predictions of the measured parameters were not biased, as determined by the mean slopes (1.00, 0.98 and 0.99, respectively), the intercepts (71 mm, 4.2 Mg/ha and −0.9 Mg/ha, respectively), or the regression slopes (0.91, 0.72, and 1.11, respectively) and were all highly correlated ($r = 0.99$). The predicted seasonal soil water evaporation from treatment 1 was 239 mm, which agrees with the predicted value of 230 mm based on the value of K_d for aerial dry matter yield and ET_m (838 mm). The average difference between the model prediction of seasonal ET, aerial dry matter yield and grain yield was 2 mm, 0.30 Mg/ha and 0.14 Mg/ha, respectively. Although the model was adjusted to fit the measured data, the main input data (weather data and soil data) are basically independent and the same as described in Steiner et al. (1987). The plant genetic parameters are similar to those in Jones and Kiniry (1986) for similar genotypes of corn. The only "real" change in the plant growth part of the model was to increase the specific leaf area to more reasonable values between 16 m^2/kg and 22 m^2/kg, which are similar to values for corn from Van Keulen (1986); and the "main" change in the water balance calculations was in the potential ET estimation.

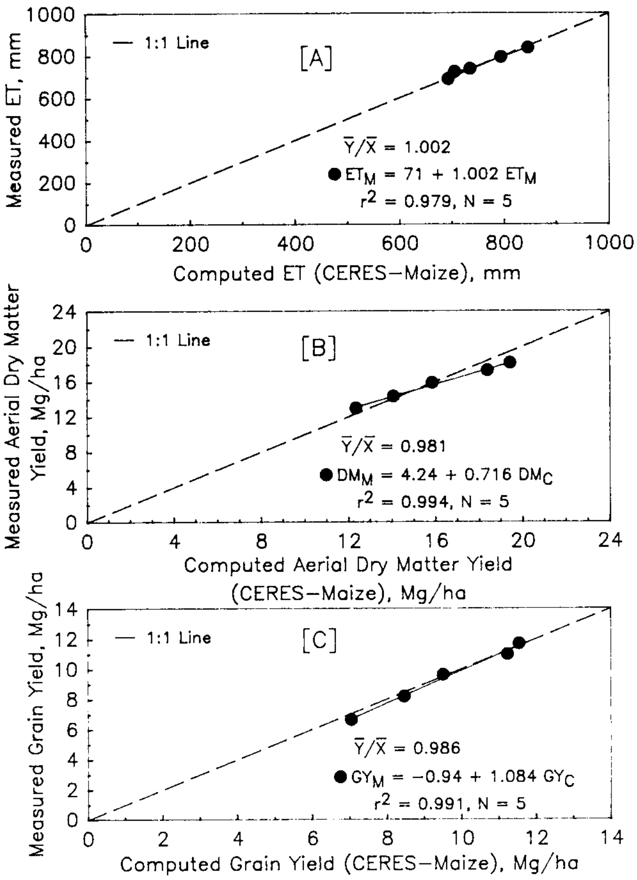

Fig. 5—Comparison of the measured ET [A], aerial dry matter yield [B], and grain yield [C] of each of 1987 sprinkler-irrigated corn treatments to the simulated parameters from the CERES-Maize model.

Sprinkler Water Management Simulations

The various water management simulations used actual weather data for Bushland for the time period from 1958 through 1985 and soils and plant data from the 1987 simulations (Table 1). It is emphasized that these results are applicable only to the slowly permeable soils in this region which have a 12% to 13% plant-extractable water holding capacity and to conventional sprinkler irrigation systems. Mean corn growing-season precipitation for the 28 years was 384 mm, and the standard deviation was 127 mm. The corn growing-season precipitation at Bushland for these 28 years is more normally distributed among the years than the monthly precipitation totals which are highly skewed (the mean precipitation is much greater than the mode). Six years had significantly lower precipitation than the mean, while only 2 years had precipitation significantly greater than the mean. Corn is not grown in this area under dryland production. The mean simulated dryland corn yields for these 28 years were 1.43 Mg/ha and 1.26 Mg/ha with full and one-half full soil water profiles, respectively, on April 1; standard deviations were 2.16 Mg/ha and 1.88 Mg/ha, respectively, and over one-half of the years produced no grain yield. Clearly, the dryland simulations substantiate that corn is not well suited to dryland production in the Southern Great Plains and that irrigation is critical to obtaining economic production of corn.

Fig. 6 shows the expected relative corn grain yield

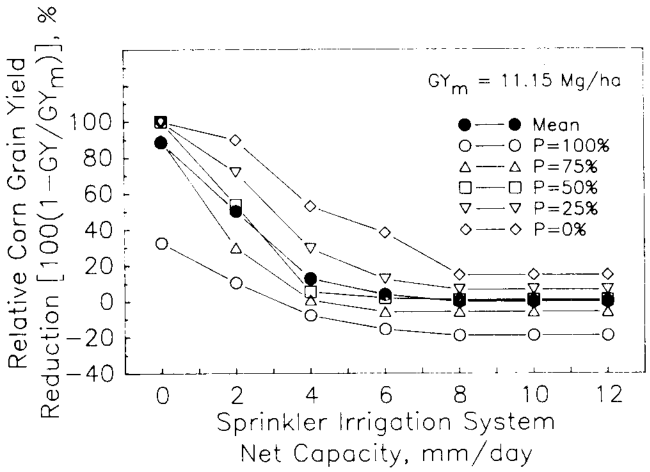

Fig. 6—Simulated relative corn grain yield reduction for Bushland, TX, on the Pullman clay loam soil as affected by net sprinkler irrigation system capacity for 20-mm net irrigation applications with a 75-mm allowable soil water profile depletion. The P values are exceedence probabilities for the relative corn grain yield reductions.

reduction in relation to the sprinkler irrigation system capacity for 20-mm irrigation applications, 75-mm allowed soil water depletion (38% of the plant extractable soil water) and one-half full soil water profile on April 1. The simulated results agree well with those of Von Bernuth et al. (1984) and Heermann et al. (1974). Net irrigation water supply capacities above 8 mm/d do not result in any improvement in yield of corn at Bushland. However, the risk of reduced corn yields is increased with a net water supply capacity below 8 mm/d. Although the mean grain yield is reduced only 4% with a reduced net supply capacity from 8 mm/d to 6 mm/d, the variance of the yield is increased 275%. These results are similar to the ones from Von Bernuth et al. (1984) using their "latest date" irrigation strategy. Assuming the average application efficiency may be 80% for sprinkler systems in this region and allowing 5% for system downtime, the gross irrigation supply capacity to adequately irrigate corn in this environment would approach 10.7 mm/d (0.42 in./d or 7.9 gpm/ac). As the irrigation supply capacity declines below 8 mm/d (0.31 in./d or 5.9 gpm/ac), yield reduction risks are greatly increased. It is interesting to note that the climatic variation effect on the simulated corn yields in this environment with adequate irrigation supply capacity is ±20% of the mean yield (11.15 Mg/ha).

Although management decisions can significantly affect crop yield, as discussed by Von Bernuth et al. (1984), our results, like theirs, indicate that the main effects may be related to how much irrigation water is required and how much of the received precipitation can be stored and held on the field. Fig. 7 shows the net seasonal irrigation requirement for corn irrigated with 20-mm applications and 75-mm allowed soil-water depletion as constrained by net irrigation system capacity and influenced by preplant profile soil water contents. Essentially, reduced preplant soil water levels simply resulted in earlier seasonal irrigations and more seasonal irrigations, nearly in proportion to the preplant soil water profile depletion. Minor effects on yield were determined when the net irrigation supply capacity was below 8 mm/d and when the irrigation interval was

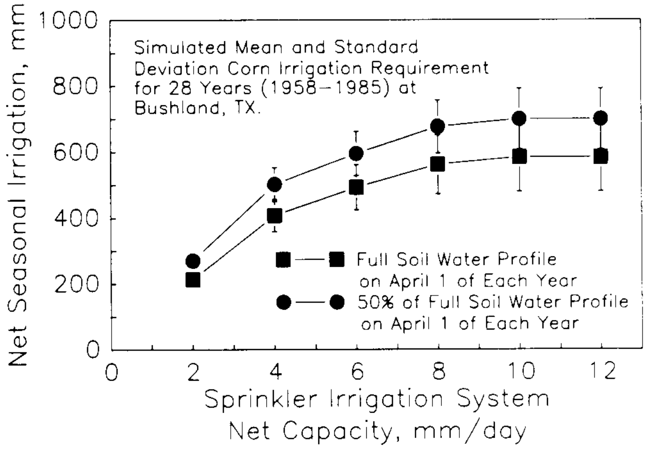

Fig. 7—Simulated net seasonal irrigation requirements for corn at Bushland, TX, as affected by net sprinkler irrigation system capacity and preplant profile soil water content for 20-mm net irrigation applications with a 75-mm allowable soil water profile depletion.

reduced from 4 days per pivot revolution to 1 day per revolution; but runoff was dramatically increased with larger irrigation applications and longer irrigation intervals, due mainly to storm runoff when precipitation events follow and/or occur during irrigations. Irrigation intervals of 2 to 3 days appeared to minimize the yield reduction and the runoff increase when 10% to 20% of the soil water storage profile was available to store precipitation. However, sprinkling at 2- to 3-day intervals can increase the ET by increasing soil water evaporation, particularly for irrigations before full ground cover is established. Therefore, net irrigation application depths approaching 24 mm to 32 mm (irrigation intervals of 3 to 4 days) or greater should be used to minimize soil water evaporation if the irrigations and the precipitation can be efficiently stored in the profile, thereby minimizing drainage and runoff losses. Soil water depletion levels up to 50% of the profile plant extractable soil water (100 mm for Pullman soil) did not decrease mean yield. Clearly, these results are limited to what might be classified as "conventional" sprinkler irrigation; and results would be expected to be quite different for LEPA systems or for various tillage systems and for other soil conditions.

SUMMARY AND CONCLUSIONS

Corn is a major irrigated crop in the Southern Great Plains that requires more irrigation water than drought-tolerant crops like cotton, grain sorghum or winter wheat and is more yield sensitive to water deficits. The irrigation system capacity is important in determining the amount of land that can be irrigated without soil water deficits reducing grain yields. Sprinkler-irrigated crop yields, water use and water use efficiency should be similar to those on similar soil types under surface irrigation. Under a full-irrigation regime, sprinkler irrigated corn at Bushland, TX, on Pullman clay loam soil in 1987 yielded 11.7 Mg/ha of grain, used 838 mm of water, and produced a water-use efficiency of 1.40 kg/m^3. Yield, water use and water use efficiency declined with decreasing irrigation.

The CERES-Maize model with some modifications accurately similated the water use, aerial dry matter yield and grain yield of sprinkler-irrigated corn in the 1987 growing season environment. The model accurately determined the major crop phenological dates of emergence, silking and physiological maturity. Additional tests of the model are currently being conducted.

Sprinkler irrigation management was simulated by the CERES-Maize model for a 28-year time period using historical weather data for Bushland, TX, to study interactions between net irrigation application depth, allowed soil water profile depletion and irrigation system supply capacity. The simulations illustrated that sprinkler-irrigated corn in this environment and for the slowly permeable soils with their large water-holding capacity in the region would require a net irrigation capacity of at least 8 mm/d to avoid yield reductions. However, much lower net irrigation capacities could be used (down to 4 mm/d to 6 mm/d) with small effects (less than 15% reductions) on mean yield if the grower is willing to accept the much greater risks of large yield reductions (up to 60%) in some years. Although, the "optimum" irrigation decisions are complex and will differ as the risk adversions of the growers differ, it appears that in the Southern Great Plains, a gross irrigation capacity of about 9 mm/d to 11 mm/d (0.35 in./d to 0.43 in./d or 6.7 gpm/ac to 8.2 gpm/ac) is necessary to avoid yield reductions. For high, dependable corn yields in this region, net seasonal irrigation requirements might range from 400 mm to 600 mm, depending on preplant soil water contents and growing season precipitation. Net irrigation application amounts of up to 20 mm to 30 mm, depending on runoff and deep percolation (which will be affected by tillage, surface residue management, etc.), should minimize water losses to soil water evaporation and storm runoff losses. Seasonal soil water profile depletions of up to 100 mm (50% of the profile plant-extractable soil water) before irrigation on Pullman clay loam soil did not reduce simulated corn yields with net irrigation capacities of 8 mm/d or greater.

References

1. Baker C.H, and R.D. Horrocks. 1976. CORNMOD, a dynamic simulator of corn production. *Agric. Systems* 4:57-77.

2. Boggess, W.G. and J.T. Ritchie. 1988. Economic and risk analysis of irrigation decisions in humid regions. *J. Prod. Agric.* 1(2):116-122.

3. Childs, S.W., J.R. Giley and W.E. Splinter. 1977. A simplified model of corn growth under moisture stress. *Transactions of the ASAE* 20(5):858-865.

4. Dierckx, J. et al. 1988. Simulations of the soil-water dynamics and corn yields under deficit irrigation. *Irrig. Sci.* 9(2):105-125.

5. Doorenbos, J. and A.H. Kassam. 1979. Yield response to water. Irrig. Drain. Paper No. 33. Food and Agriculture Organization of the United Nations, Rome, Italy.

6. Doorenbos, J. and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements. Irrig. Drain. Paper No. 24 (Revised). Food and Agriculture Organization of the United Nations, Rome, Italy.

7. Dugas, W.A. and C.G. Ainsworth. 1985. Effect of potential evapotranspiration estimates on crop model simulations. *Transactions of the ASAE* 28:471-475.

8. Duncan, W. G. 1975. SIMAIZ: A model simulating growth and yield in corn. In *An application of system method to crop production*, D. N. Baker, P. B. Creech and F. G. Maxwell, ed., 34-48. Mississippi Agric. Frestry Exp. Stn., State College, MS.

9. Du Pisani, A.L. 1987. The CERES-Maize model as a potential tool for drought assessment in South Africa. *Water South Africa* 13(3):159-164.

(continued on page 160.)

Sprinkler Irrigation Management for Corn— Southern Great Plains

(continued from page 154.)

10. Eck, H.V. 1984. Irrigated corn yield response to nitrogen and water. *Agron. J.* 76:421-428.

11. Hanks, R.J. and V.P. Rasmussen. 1982. Predicting crop production as related to plant water stress. *Adv. Agron.* 35:193-215.

12. Heermann, D.F., H.H. Shull and R.H. Mickelson. 1974. Center pivot design capacities in eastern Colorado. *J. Irrig. Drain. Div.*, ASCE 100(IR2):127-141.

13. Hodges, T. et al. 1987. Using the CERES-Maize model to estimate production for the U.S. cornbelt. *Agric. Forest Meteorol.* 40:293-303.

14. Jones, C.A. and J.R. Kiniry, eds. 1986. *CERES-Maize, a simulation model of maize growth and development.* College Station: Texas A&M Univ. Press.

15. Kundu, S.S., G.V. Skogerboe and W.R. Walker. 1982. Using a crop growth simulation model for evaluating irrigation practices. *Agric. Water Mgmt.* 5:253-268.

16. Lambert, J.L. and D.C. Reicosky. 1984. Dynamics of water in *Zea mays* L.: Sensitivity analysis of TROIKA. *Transactions of the ASAE* 27(1):117-124.

17. Lyle, W.M., and J.P. Bordovsky. 1983. LEPA irrigation system evaluation. *Transactions of the ASAE* 26(3):776-781.

18. Morgan, T.H. A.W. Biere and E.T. Kanemasu. 1980. A dynamic model of corn yield response to water. *Water Resour. Res.* 16(1):59-64.

19. Musick, J.T. and D.A. Dusek. 1980. Irrigated corn yield response to water. *Transactions of the ASAE* 23(1):92-98, 103.

20. Musick, J.T., et al. 1988a. Long-term irrigation trends — Texas High Plains. ASAE Paper No. SWR 88-103. St. Joseph, MI: ASAE.

21. Musick, J.T., F.B. Pringle, and J.D. Walker. 1988b. Sprinkler and furrow irrigation trends — Texas High Plains. *Applied Engineering in Agriculture* 4(1):46-52.

22. Priestley, C.H.B., and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Rev.* 100:81-92.

23. Ritchie, J.T. 1972. A model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8(5):1204-1213.

24. Seginer, I. 1983. Irrigation uniformity effect on land and water allocation. *Transactions of the ASAE 26(1):116-122.*

25. Stapper, M. and G. F. Arkin. 1980. CORNF: *A dynamic growth and development model for maize (Zea mays* L.*).* Res. Ctr. Program and Model Doc. No. 80-2. Texas Agric. Exp. Stn., College Station:

26. Stegman, E.C. and A.M. Shah. 1971. Simulation versus extreme value analysis in sprinkler system design. *Transactions of the ASAE* 13(3):486-491.

27. Steiner, J.L., J.R. Williams and O.R. Jones. 1987. Evaluation of the EPIC simulation model using a dryland wheat-sorghum-fallow crop rotation. *Agron. J.* 79:732-738.

28. Stockle, C. and G. Campbell. 1985. A simulation model for predicting effect of water stress on yield: an example using corn. *Adv. Irrig.* 3:283-311.

29. Taylor, H.M. et al. 1963. *Soils of the Southwestern Great Plains Field Station.* misc. Publ. MP-669. College Station: Texas Agric. Exp. Stn.

30. Undersander, D.J., T.H. Marek and R.N. Clark. 1985. Effect of nozzle type on runoff and yield of corn and sorghum under center pivot sprinkler systems. *Irrig. Sci.* 6:107-116.

31. Unger, P.W. and F.B. Pringle. 1981. *Pullman soil: Distribution, importance, variability, and management.* Bull. B-1372, College Station: Texas Agric. Exp. Stn.

32. USDA-SCS. 1972. Hydrology. In *National Engineering Handbook.* Sec. 4, Ch. 10. Soil Conserv. Serv., Washington, DC.

33. Van Keulen, H. 1986. Plant data. 234-247. In *Modelling of agricultural production: Weather, soils, and crops.*234-247. Simulation Monogr., Ctr. Agric. Publ. Documentation. Wageningen. The Netherlands.

34. Von Bernuth, R.D. et al. 1984. Irrigation system capacities for corn production in Nebraska. *Transactions of the ASAE* 27(2):419-424, 428.

35. Warrick, A.W. 1984. Interrelationships of irrigation uniformity terms. *J. Irrig. Drain. Eng.* 109(3):317-322.

36. Wenda, W.I. and R.J. Hanks. 1981. Corn yield and evapotranspiration under simulated drought conditions. *Irrig. Sci.* 2:193-204.

37. Williams, J.R., C.A. Jones and P.T. Dykes. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Transactions of the ASAE* 27(1):129-144.